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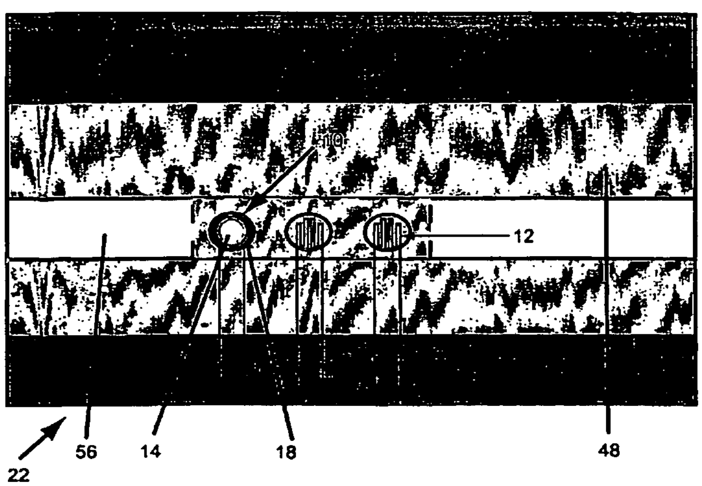
(54) Title: MICRO-FLUIDIC PUMP



(57) Abstract: A micro-fluidic pump (22) has a pulsating micro chamber (46) which includes a walled chamber (50). The walled chamber further includes at least one pulsating portion (52) actuable to pulse and change an interior volume of the walled chamber. An actuating mechanism (10) peristaltically moves fluids through a micro conduit (56). The actuating mechanism includes a closed pocket (11) adjacent to the conduit. A flexible mechanism (18) defines a portion of a wall of the micro conduit (56). An expanding mechanism (14) which is understood to be a fluid is disposed within the pocket (11) for expanding a volume of the pocket and thereby flexing the flexible mechanism (18) into the micro conduit thereby changing the volume of the conduit (56).

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MICRO-FLUIDIC PUMP

BACKGROUND OF THE INVENTION

1. TECHNICAL FIELD

The present invention relates to mechanical pumps. More specifically, the present invention relates to mechanical micro-fluidic pumps for use in moving fluids.

2. BACKGROUND ART

An actuator that produces out of plane movement is necessary for many chip-scale ($1mm^2$ to $1cm^2$) applications. Some of these applications include: movement of small volumes of liquid using a micro-fluidic peristaltic pump, valving of solutions to deliver different chemicals to an area on a chip, mixing of solutions in a microscopic chamber, as well as through the attachment to other devices like cilia, fans, or other devices to produce out of plane motion for a silicon micro-machined chip.

Typically, actuators are the driving mechanism behind pumps that force fluid through a passageway, channel, port, or the like, and can possibly function as valves in micro-fluidic devices. These actuators work by various types of actuation forces applied to a flexible mechanism, valve or other similar device. Actuation occurs through methods using various forces such as electrostatic, piezoresistive, pneumatic, electrophoretic, magnetic, acoustic, and thermal gas expansion.

Electrostatic actuation of a membrane is one of the fastest methods for pumping solutions through a system. Piezoresistive actuation is also very fast, utilizing hybrids of thick and thin films to produce a resonant structure affecting pumping of solutions. While these devices exhibit very fast actuation rates, they require very high voltages, from 100V to 200V, and 50V to 500V respectively. Additionally, electrostatic and piezoresistive actuation require specialized valves

that direct fluid flow in a particular direction. As a result, these pumps require three chips to be separately machined and bonded together to produce the device.

Pneumatic actuation requires an external pressurized gas source to actuate the membranes that cause fluid flow. While this method is feasible in a laboratory setting where pressurized gas is available, it is impractical for in-the-field utilization.

Electrophoretic actuation utilizes electrodes within a solution to impart a motive force to charged molecules within the solution. Neutral molecules are then 'dragged' along with the charged particles. This method is amenable to size reduction; however, it does have critical side effects such as the chromatographic phenomenon that causes a separation of molecules based upon charge. Additionally the high voltages necessary to induce fluid transport are incompatible with standard CMOS circuitry.

Ultrasonic actuation occurs through flexural plate waves. This methodology however, is inefficient and causes mixing due to enhanced diffusion.

Thermal gas expansion relies on the expansion of trapped air in the system to move fluid through the conduits 56. This is accomplished by selectively producing hydrophobic and hydrophilic regions on the chip.

The devices from these previous bodies of work lack the ability to cost-effectively add integrated sensors or circuitry to the devices. Integrating circuitry incorporated into the micro-fluidic devices reduces: (1) the need for costly instrumentation, (2) the overall power consumption of the system, and (3) the complexity of the control signals and mechanisms. Additionally, integrated circuitry allows for the addition of chemical and physical sensor arrays, and for connection to telemetry systems for remote communication with external devices.

Most, if not all, of the micro-fluidic actuators are produced on structures that are not planar. (See, U.S. Patents 5,962,081 and 5,726,404). Various other efforts are also underway to build miniature valves and pumps in silicon for

micro-fluidics. It has been difficult to produce good sealing surfaces in silicon, and it turns out that these valves, although in principle can be mass-produced on a silicon wafer, require expensive packaging to be utilized. Consequently, such micro-fluidic components cannot be considered inexpensive and/or disposable. In addition, these micro-fluidic pumps and valves must be interconnected into systems including sensors, electronic controls, telemetric circuitry, etc. such that the interconnection becomes expensive.

Accordingly, it would therefore be useful to develop a micro-fluidic pump that is mobile, planar, and overcomes the problems found in the prior art.

SUMMARY OF THE INVENTION

According to the present invention, there is provided a pulsating micro chamber including a walled chamber. The walled chamber further includes at least one pulsating portion actuable to pulse and change an interior volume of the walled chamber. The present invention further provides for a micro-fluidic pump including a micro conduit for carrying fluid therethrough and at least one actuating mechanism for peristaltically moving fluids through the micro conduit. The actuating mechanism includes a closed pocket adjacent to the conduit, a flexible mechanism defining a portion of a wall of the micro conduit, and an expanding mechanism disposed within the pocket for expanding a volume of the pocket and thereby flexing the flexible mechanism into the micro conduit thereby changing the volume of the conduit.

DESCRIPTION OF THE DRAWINGS

Other advantages of the present invention are readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

Figure 1 is a diagram showing peristaltic firing pattern for micro-fluidic pump actuation;

Figure 2 is a cross-sectional schematic view of the micro-fluidic device with approximate dimensions;

Figure 3 is a temperature profile through each layer identified in Figure 2;

Figure 4 is a temperature profile to the cross-section of the device of the present application;

Figure 5 is a CAD layout of the micro-actuator of the present invention;

Figure 6 A and B are the pressure and temperature curve fitting for steam;

Figure 7 shows three micro-fluidic actuators in succession, thus creating a micro pump of the present invention;

Figure 8A and 8B show a perspective view of the pulsating micro chamber of the present invention; and

Figure 9 is schematic diagram of an embodiment of a micro-fluidic pump.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides for a pulsating micro-chamber 46 and a micro-fluidic pump generally shown at 22.

In general, the present invention is useful in all applications where small quantities of fluids need to be dispensed, mixed, reacted, heated or cooled, or the reaction products inspected. Such applications occur in clinical and diagnostic testing, environmental or forensic testing, analytical chemistry, fine chemistry, biological sciences, and combinatorial synthesis. The micro-fluidic pump can be used in a micro-fluidic system that has a simplified network of tubes and pumps, usually associated with present liquid delivery systems capable of performing such processes.

The minimum volume the present invention can deliver is less than 5 nL. An estimated maximum flow-rate based on the thermal dissipation of the actuator and the volume pumped is approximately 300-500 μL/min. This rate however, is not limiting and thus can be decreased or increased without departing from the spirit of the present invention.

While accurate dispensing of very small volumes and consistent flow-rates are desirable in many applications, the micro-fluidic pump 22 can be used in settings, including, but not limited to, drug delivery to individual cells in a cell culture where extremely low volume needs to be delivered; capillary electrophoresis when the column needs to be pumped past a detector; pumping a reference solution to calibrate chemical sensors in a small volume device; and miniaturized chemical analysis systems where precise volumes of chemicals need to be mixed.

The terms "actuator" and "actuating mechanism" 10 as used herein are meant to include, but are not limited to, a device that causes something to occur. The actuator 10 activates the operation of a valve, pump, or other microscopic device. Typically, the actuator 10 affects fluid flow rates within a chamber and can be aided by capillary action to draw fluids through the system. The actuator 10 has no true minimum flow rate capability in that a single 5 nl pulse of can be

initiated. In fact, with current fabrication technologies,the pulse can be as low as 400 pL. Current maximum flow rate is approximately 100 µl/min; however, this value can be increased several orders of magnitude through redesign without departing from the spirit of the present invention. Additionally, the actuators 10 utilize very low power consumption. For instance, less than 680 µW of power is required to pump fluid at 10 µl/min on a continuous basis.

The term "closed cavity" 11 as used herein is meant to include, but is not limited to, a sealed cavity that contains a liquid or solid expanding mechanism 14 that is expanded or vaporized to generate expansion or actuation of a flexible mechanism 18. The closed cavity 11 must be completely sealed in order to contain the expansion therein, and must be flexible on at least one side.

The term "expanding mechanism" 14 as used herein, is meant to include, but is not limited to, a fluid 14 capable of being vaporized and condensed within the closed cavity 11. The expanding mechanism 14 operates upon being actuated or heated. The expanding mechanism 14 includes, but is not limited to, water, wax, hydrogel, hydrocarbon, and any other similar substance known to those of skill in the art.

The term "flexible mechanism" 18 as used herein is meant to include, but is not limited to, any flexible mechanism 18 that is capable of expanding and contracting with the vaporization and condensation of the expanding mechanism 14. The flexible mechanism 18 must be able to stretch without breaking when the expanding mechanism 14 is vaporized. The flexible mechanism 18 is made of any material including, but not limited to, silicon rubber, rubber, PVC, polyurethane, polymers, combinations thereof, and any other similar flexible mechanism known to those of skill in the art.

The term "heating mechanism" 12 as used herein is meant to include, but is not limited to, a heating device or element 12 that is incorporated with the actuator 10 of the present invention. The heating mechanism 12 generates heat to induce expansion of the expanding mechanism 14. The heating mechanism 12 is disposed adjacently to the flexible mechanism 18 in order to turn on and off as well as maintaining on and off selective expansion of the expanding

mechanism 14. Generally, the heating mechanism 12 is formed of materials including, but not limited to; polysilicon, elemental metal, silicide, or any other similar heating elements known to those of skill in the art. Typically, the heating mechanism is encased in a medium such as SiO_2. The heating mechanism 12 can be powered using any power source known to those of skill in the art, but requires very low power to achieve sufficient temperatures for vaporization of the expanding mechanism 14. It is necessary to utilize low power devices and circuitry to conserve energy and allow the use of very small lightweight film or button batteries.

The term "temperature sensor" 16 as used herein, is meant to include, but is not limited to, a device designed to determine and monitor temperature. The temperature sensor 16 is made from material including, but is not limited to, polysilicon, elemental metal, silicide, and any other similar material known to those of skill in the art. Typically, the temperature sensor 16 is situated within or near the heating element of the heating mechanism 12. The temperature sensor 16 ensures that the heating mechanism 12 is maintained within proper parameters as determined by one of skill in the art. A resistive temperature sensor 16 can be formed of polysilicon, elemental metal, or silicide; however, other materials, or methods of temperature sensing (i.e., thermocouple) known to those of skill in the art can also be used.

The terms "chamber," "micro chamber," "pulsating micro chamber," "micro conduit," and "conduit" as used herein are meant to include, but not limited to, any type of tube, pipe, planar channel, conduit, or any other similar chamber known to those of skill in the art. The chamber has a wall mechanism made from material including, but not limited to, glass, silicon, rubber, silicone, plastics, metal, ceramics, polymers, combinations thereof, and any other similar material known to those of skill in the art. As for the wall mechanism, it further includes a pulsating portion that is integral with the wall mechanism. The pulsating portion similarly is made from materials including, but not limited to, rubber, silicone, plastics, polymers, and any other similar flexible material known to those of skill in the art. In one embodiment, the chamber encompassing the micro-actuator is

etched out of glass in a nearly hemispherical shape. A variety of conformations of spherically cut patterns (i.e. 1/3 of a sphere, ½ of a sphere, etc.) with differing radii and footprints are employed to provide different pumping and valving characteristics.

As previously described, one embodiment of the present invention is a pulsating micro-chamber 46. The pulsating micro-chamber 46 includes the wall 50 defining the chamber 46. The wall further includes at least one pulsating portion 52 actuable to pulse and change the interior volume 48 of the chamber defined by the wall 50. The pulsating portion 52 can be a part or portion of the wall 50 or can be added to the wall 50 in order to provide a pulsating portion 52 thereof. For example, the wall 50 can include an opening therethrough and a membrane or other flexible material disposed over the opening (Figure 8).

Once actuated, the pulsating portion 52 of the pulsating micro-chamber 46 changes the interior volume 48 of the chamber 46. The volume can be decreased or increased depending upon the mode of actuation. In one embodiment, the pulsating portion 52 is actuated by either being heated or cooled. If heated, the pulsating portion 52 expands and thus decreases the interior volume 48 of the chamber 46. If cooled, then the pulsating portion contracts and thus increases the volume 48 of the chamber 46. The increase in volume can create a lower pressure therein and cause a vacuum effect to draw fluids into the chamber 46 therein. Thus, by heating and cooling, vaporizing and/or condensing of the expanding mechanism 14 occurs in the closed cavity 11 to cause expansion and/or contraction.

Another embodiment of the present invention is a micro-fluidic pump 22 that includes a micro conduit 56 for carrying fluid therethrough and at least one actuating mechanism 10 for peristaltically moving fluids through the micro conduit 56. The actuating mechanism 10 includes a closed pocket 11 adjacent to the conduit, a flexible mechanism 18 defining a portion of a wall of the micro conduit, and an expanding mechanism 14 disposed within the pocket for expanding a volume of the pocket and thereby flexing the flexible mechanism 18 into the micro conduit thereby changing the volume of the conduit 56. In this

embodiment, the micro-fluidic pump 22 includes three micro-fluidic actuators 10 placed in series and connected through the micro conduit 56. Each actuator 10 is actuated through an integrated circuit or computer control to provide peristaltic pumping action.

Just as in the pulsating micro chamber 46, the actuating mechanism 10 of the micro fluidic pump 22 of the present invention causes a change in volume within the conduit 56. The volume can be either increased or decreased depending upon the mode of actuation. In one embodiment, the actuating mechanism 10 can either be activated or deactivated to cause actuation. For example, if the heating mechanism 12 of the actuating mechanism 10 is initially activated, then the heat created induces the expansion of the expanding mechanism 14 via vaporization of the expanding mechanism within the closed cavity 11. As a result, the expanding mechanism 14 then causes the flexible mechanism 18 to expand into the micro conduit 56 and thus cause a decrease in volume within the micro conduit 56. Alternatively, the heating mechanism 12 can be in an activated state to keep the expansion mechanism 14 in an expanded state. Then, when the heating mechanism 12 is inactivated, the flexible mechanism 18 contracts and increases the volume within the micro conduit 56 via condensation of the expanding mechanism 14 in the closed cavity 11. Thus, the increase in volume can create a lower pressure therein and cause a vacuum effect to draw fluids into and through the micro conduit 56.

Factors affecting design of the actuators 10 include physical layout, actuation timing, and electrical current and heat generation/dissipation requirements for actuation. The optimal firing order and timing for each actuator 10 depends upon the requirements of the system and are under digital control to create the peristaltic pumping action. By strategically placing these actuators 10 in the fluid flow channels, different solutions can be pumped or actively stopped creating an effective fluidic multiplexer. This allows different solutions to be pumped to reaction chambers while maintaining a seal against cross contamination. Schematics of the micro-pumps are provided in Figure 7 and 9.

Timing for actuation of the micro pumps 22 were modeled, based upon expansion times of 150 μs and contraction times of 4.73 ms, as determined through the mathematical modeling. To effect peristaltic flow, control of the individual actuators 10 of the pump 22 is under computer control or integrated circuitry. The peristaltic firing pattern is depicted in Figure 1. To achieve a flow rate of 10 μL/min, each actuator 10 must expand and contract within 14.9 ms. Mathematical models indicate that the actuators 10 can supersede this requirement. However, to maintain the actuator 10 in the actuated state for a longer period of time and thereby slow down the system, square wave pulses of energy are applied to the actuator 10. In this manner, the energy applied to the heating mechanism 12 is minimized to prevent overheating of the solution.

The simple, planar actuation described above for the liquid delivery system can be used as a component in assembling much more complex micro-fluidic systems. The single pump 22 and reservoir can be extended to multiple reservoirs, which can be connected through capillaries and pumps 22 to form a single integrated assembly.

In an embodiment of the present invention, optical or electronic beam (E-beam) photo masks are used and silicon wafers containing micro pumps are fabricated. The micro-fluidic chips are to have a 2-sided alignment of wafers, micro-machining and silicon processing. Through the use of an arbitrary wave-form generator, and/or computer controlled digital-to-analog (d/a) and analog-to-digital (a/d) PCI computer cards (for example, the PCIMIO16XH, National Instruments), the micro fluidic pumps are controlled to have optimal operating parameters (i.e. stimulatory waveform patterns) to generate peristaltic pumping action. Electronic control of the peristaltic pumps 22 is optimized to maximize flow rates, maximize pressure head, and minimize power utilization and heat generation. Other parameters to be evaluated include the temperature profile of the medium being pumped. Initially, square wave pulses are utilized. Alternatively, to minimize and/or additionally power consumption and heat generation, a resistor-capacitor circuit is utilized to exponentially decrease the voltage of the sustained pulse. Further, pulses of modified square waves can be

utilized to increase the duration of activation while minimizing power requirements and heat generation.

The maximum pressure produced by the pumps 22 at different pumping rates is determined by testing the capabilities of the pumps to cause flow through the system. To effect testing, the effluent from the micro-fluidic chip is connected to a vertical tube, and the maximal height the medium can achieve provides a measure of the maximal pressure-head developed. Alternatively, a small pressure sensor is used to verify pressure generation throughout the device.

In addition to the micro conduit 56, an important aspect of the micro-fluidic pump 22 is the actuating mechanism 10. Typically, in an embodiment of the present invention, the pump 22 has three actuating mechanisms 10. Each one produces a pulse and works in tandem with the other actuating mechanisms 10 to produce peristaltic pumping action. The actuating mechanisms 10 are operatively connected to each other through the micro conduit 56.

The actuating mechanism 10 of the micro-fluidic pumps 22 is designed such that it can be fabricated using minimal micro-machining and employs planar fabrication techniques. The micro-fluidic actuator 10 is based upon electrically activated pneumatic actuation of the flexible mechanism 18 made by being micro-screen-printed, spin coated, dispensed, or the like.

The advantage of pneumatic actuation is that large deflections can be achieved for the flexible mechanism 18. To actuate the flexible mechanism 18, the expanding mechanism 14 is heated and converted into vapor to provide the driving force. Utilizing an integrated heating mechanism 12, the expanding mechanism 14 is vaporized under the flexible mechanism 18 to provide the pneumatic actuation. This actuation occurs without the requirement of utilizing external pressurized gas.

The fluid being pumped serves the purpose of acting as a heat sink to condense the gas back to liquid and hence return the flexible mechanism 18 to is relaxed state when the heating mechanism 12 is inactivated. A temperature

sensor 16 is integrated adjacent to the actuator 10 to monitor the temperature of the micro-fluidic integrated heating mechanism 12 and hence, expanding mechanism 14.

The heating mechanism 12 requires very low power to achieve sufficient temperatures for fluid vaporization. As an example, miniature inkjet nozzles that require temperatures in excess of 330° C, utilize 20μ second pulses of 16 mA to heat the fluid and fire an ink droplet. Considerably lower power would be required to vaporize the liquid in the present micro-fluidic pump application. In the field, it is necessary to utilize low power devices and circuitry to conserve energy and allow the use of very small, lightweight batteries.

Once the heating mechanism 12 is activated, vaporization of the expanding mechanism 14 takes place. The expanding mechanism 14 component imposes a pressure upon the flexible mechanism 18 causing it to expand and be displaced above the heating mechanism 12 and reduce the volume of the chamber 20. This methodology can be utilized to displace fluid between the flexible mechanism 18 and the walls of the chamber 20 (pumping action), to occlude fluid flow through the chamber 20 (valving action), to provide direct contact to the glass substrate to effect heat transfer, or to provide the driving force for locomotion of a physical device (i.e., as in a walking caterpillar and/or a swimming paramecium with a flapping flagella, in which case the glass chamber 20 encompassing the micro-actuator 10 would not be used).

The heat flux through each of the layers composing the device is calculated using existing boundary conditions. In one specific embodiment, with regard to heat transfer through the system, the boundary conditions are body temperature (for the heat sink) and the temperature required to vaporize the expanding mechanism 14 (for the heat source). These values however, vary according to the appropriate application. Thus, the values can be considerably lower.

Due to the differences in heat transfer through liquid versus gas, approximately twice as much heat flux travels through the device when the expanding mechanism 14 is all liquid compared to all vapor. In order to reduce

heat dissipation into the fluid being pumped, while the expanding mechanism 14 is in the liquid state, the heating mechanism 12 is quickly ramped to the temperature required to vaporize the liquid. The expanding mechanism 14 is vaporized to the extent that the flexible mechanism 18 contacts the opposite side of the micro conduit 56. Then, heat transfer to the medium being pumped is minimized.

It is assumed that the temperature on both sides of the SiO_2 that encapsulates the heating mechanism 12 is constant, and that heat flux in each direction is dependent upon the heating mechanism 12 temperature and the resistance to heat flow either through the device or to the air from the backside. A schematic of the cross section of the entire device is provided in Figure 9. Steady state heat flow through the entire actuator 10, for the fully actuated state, the intermediate state, and the resting state are modeled. The temperature profiles are presented graphically in Figures 2 and 3, and in a tabular format in Table 1.

The temperature of the saturated liquid hydrogel, at 1 ATM, is assumed to be 100° C. The heat flux to the air, through the back of the heating mechanism 12, is calculated to be 1263 W/K-m^2. The total heat flux through the device is calculated to be 46,955 W/K-m^2 with a total flux from the heating mechanism 12 of 48,218 W/K-m^2 (i.e. 97% efficiency of focused heat transfer). The temperature of the inactive state hydrogel varies between 86° and 94° C.

The temperature of the activated, vapor state hydrogel is approximately 120°C, which is the saturation temperature for steam at 2 ATM. The heat transfer coefficient for convection can be calculated directly from the thermal conductivity. The heat flux to the air through the back of the heating mechanism 12 is 2818 W/K-m^2. The heat flux through the device is 21,352 W/K-m^2 with a total flux from the heating mechanism 12 of 24,170 W/K-m^2. When the aqueous component of the hydrogel is completely in the vapor state, there is no fluid 14 in the channel and the thin film of solution between the flexible mechanism 18 and the glass is approximately 60°C.

The temperature distribution through each layer of the device was modeled using linear methods. The actual temperature distribution is exponential, but the temperatures at the interface of each layer are identical to that predicted by the linear model. Figure 3 depicts the temperatures between each layer. Figure 4 depicts how the temperature varies through the device at a specific distance. The blue line (square markers in Figure 3, tight dashed line in Figure 4) indicates the temperature profile of the fully contracted (liquid state) actuator 10, while the red line (diamond markers in Figure 3, solid line in Figure 4) indicates fully expanded (vapor state). The green line (triangle markers in Figure 3, loose dashed line in Figure 4) represents the temperature profile of the partially expanded actuator 10.

The volume of liquid hydrogel was determined based on the volume of vapor needed to expand the flexible mechanism 18 completely at 2 ATM using the ideal gas law. This assumption is valid because the temperatures and pressures are moderate. The volume of liquid hydrogel necessary to achieve this volume of gas at this pressure, assuming the hydrogel is 10% water and all of the water is completely vaporized, is 0.033 nL. In one embodiment, cylindrically shaped sections of hydrogel are utilized within the actuator 10. This shape has been chosen to optimize encapsulation by the actuator flexible mechanism 18. The cylinders have either a diameter of approximately 140 μm and a height of 2.14 μm, or a diameter of 280 μm with a height of 0.54 μm (identical volumes, different orientation to the heating element). This type of hydrogel is but just one example. Photocurable and liquid hydrogels for instance, can also be used.

In one embodiment of the present invention, for flexible mechanism 18 actuation and hydrogel vaporization, it is necessary to raise the temperature of the hydrogel from body temperature to the boiling point, 120°C at 2 ATM. Thermodynamic models indicate that approximately 8.03×10^{-7} J of heat transfer is required to raise the temperature of the hydrogel from 37°C to 120°C (1.08×10^{-7} J) and vaporize all of the water (6.95×10^{-7} J). This is consistent with the sum of enthalpy equation.

For flexible mechanism 18 contraction and hydrogel condensation, it is assumed that all heat dissipation from the activated, vaporized hydrogel, as it condenses, is transferred into the solution being pumped or valved. The calculation for this condensation involves condensing all of the water in the hydrogel plus sub cooling the hydrogel from 100°C to 90°C in order to completely contract the actuator 10. Modeling conduction through the actuator 10 flexible mechanism 18 using Fourier's equation provides a flux of 0.0015 J/s and a condensation time of 0.00473 seconds. This represents a worst case scenario, neglecting thermal conduction to the silicon substrate.

The actuator 10 design is completed, modeled, and tested. This includes the poly-silicon heating mechanism 12 design, the CAD layouts of the actuator 10, and the micro-actuator fabrication process.

Based upon the geometry of the 100 μm tall chamber 20, it was calculated that a circular actuator 10 with a diameter of 300 μm is required to deliver 4.9 nL quantities of liquid per actuation of the flexible mechanism 18. The heating mechanism 12 is laid out as a square that encompasses the majority of the circular hydrogel area without extending past the edge of the chamber 20. However, other shapes can be employed, such as circular, rectangular, or triangular layouts in which the area of hydrogel is encompassed as much as possible. In order to provide efficient micro-actuation in 150 μs, requirements for the heating mechanism 12 power output and electrical resistance were calculated. To provide the required 777 nJ of energy, the resistance of the poly-silicon heating mechanism 12 was calculated to between 450 to 500Ω, based upon utilizing a 5V power supply. Actuation requires a 150 μs pulse of approximately 11 mA of current, providing the 777 nJ of energy required. In order to achieve a pumping rate of 10 μL/minute, approximately 677 μW of power is required. In previous work, poly-silicon structures at a thickness of 6000 Å or 0.6 μm, having a resistance of 15 Ω/elemental square have been produced. To provide the required resistance, 5 poly-silicon heating mechanism 12 lines are arranged in parallel (See figure 5). The poly-silicon heating

mechanism 12 elements have a width of 5 μm. The total resistance of the heating mechanism 12 is 450 Ω.

Figure 5 is a schematic CAD layout of one embodiment with an actuator 10 including a poly-silicon heating mechanism 12. Because of its high thermal conductivity the silicon substrate acts as a heat sink. To reduce thermal conduction to the silicon substrate, a window in the silicon, located beneath the heating mechanism 12, provides the hydrogel with an isolated platform. This window is only slightly larger than the heating mechanism 12 to maintain some thermal conduction to the substrate. The opposite side of this window is exposed to air, which has a very low heat transfer coefficient, compared to any fluids being pumped. After the actuator 10 is energized, thermal conduction to the silicon provides decreased time to condense the liquid in the hydrogel. This decreased constriction time provides improved pumping rates. If the window is significantly larger than the actuator 10, there is no heat conduction path to the substrate, hence increasing condensation time and decreasing the maximal flow rate.

In an embodiment of the present invention, the solid or non-solid hydrogel is presented as a cylinder with diameter of 280 μm and height of 0.5 – 1 μm. The actuation chamber 20 encompasses the entire cavity etched in the glass substrate. The cavity can be redesigned before mask generation to account for undercut of the glass. As glass is chemically etched, the etchant undercuts the mask making the cavity larger than the photo mask size.

Fabrication of this device is based upon the development of a process flow. The fabrication process utilizes bulk silicon micro-machining techniques to produce the isolation windows, and thick film screen printing techniques for mass dispensing, spin coating, expandable mechanism, such as thick film screen printing, or dispensing of actuation membranes.

A polymeric hydrogel (or hydrocarbon) can be utilized to provide a physically supportive structure that withstands the application of flexible mechanism 18 as well as to provide the aqueous component required for actuation. Several commercially available materials meet these requirements.

A hydrogel is selected that contains approximately 30% aqueous component that vaporizes near 100°C. Several promising materials have been identified, each of which is examined for suitability in this application, including, but not limited to, hydroxyethylmethacrylate (HEMA) and polyvinylpyrrolidone (PVP). Additionally, hydrocarbons can be used since they possess lower boiling points than aqueous hydrogels, and therefore require less power to effect pneumatic actuation.

Dispensing hydrogel (or hydrocarbon) into the desired location is accomplished utilizing one of three methods. First, a promising method for patterning the hydrogel is to utilize a photopatternable-crosslinking hydrogel. The hydrogel is cross-linked by incorporating an UV photo-initiator polymerizing agent within the hydrogel that cross-links when exposed to UV radiation. Using this technique, the hydrogel would be evenly spun on the entire wafer using standard semiconductor processing techniques. A photographic mask is then placed over the wafer, followed by exposure to UV light. After the cross-linking reaction is completed, excess (non-cross-linked hydrogel) is washed from the surface.

The second method involves dispensing liquid hydrogel into well-rings created around the poly-silicon heating mechanism 12. These wells have the ability to retain a liquid in a highly controlled manner. Two photopatternable polymers have been utilized to create microscopic well-ring structures, SU-8 and a photopatternable polyimide. These well-rings can be produced in any height from 2 μm to 50 μm, sufficient to contain the liquid hydrogel. Once the hydrogel solidifies, flexible mechanisms can be deposited over them. This can be accomplished in an automated manner utilizing commercially available dispensing equipment.

In a third alternate method, a pre-solidified hydrogel is used that has been cut into the desire size and shape. This is facilitated by extruding the hydrogel in the desired radius and slicing it with a microtome to the desired height, or by spinning the hydrogel to the desired thickness and cutting it into cylinders of the

desired radius. Utilizing micro-manipulators, the patterned gel is placed in the desired area. This process can also be automated.

It is assumed that the temperature on both sides of the SiO_2 that encapsulates the heating mechanism 12 is constant, and that heat flux in each direction is dependant upon the heating mechanism 12 temperature and the resistance to heat flow either through the device or to an air pocket on the heating mechanism 12 backside. A schematic of a cross section of the actuator 10 is provided in Figure 2 and 9. Steady-state heat flow through the entire actuator, for the fully actuated state, the intermediate state, and the resting state are modeled. This data was calculated for the static case during which time no fluid flow is occurring (i.e. steady-state; the system is poised at 100° C, waiting to be initiated). The fluid temperature is greater for the contracted state since the expanding mechanism 14 conducts heat at a greater rate than water vapor. The temperature profiles illustrating the application of one embodiment are presented graphically in Figures 3 and 4.

Throughout this application, there are various publications referenced by author and year and Patents by their number. Full citations for the publications are listed below. The disclosures of these publications and patents are hereby incorporated by reference in their entirety into this application in order to describe more fully the state of the art to which this invention pertains.

The invention has been described in an illustrative manner, and it is to be understood that the terminology, which has been used, is intended to be in the nature of words of description rather than of limitation.

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is, therefore, to be understood that within the scope of the appended claims, the invention can be practiced otherwise than as specifically described.

CLAIMS

What is claimed is:

1. A pulsating micro chamber comprising wall means for defining said chamber, said wall means including at least one pulsating portion actuable to pulse and change an interior volume of said chamber defined by said wall means.

2. The chamber according to claim 1 selected from the group consisting essentially of a tube, pipe, planar channel, and conduit.

3. The chamber according to claim 1, wherein said wall means is made from material selected from the group consisting essentially of glass, silicon, rubber, silicone, plastics, metal, ceramics, polymers, and combinations thereof.

4. The chamber according to claim 1, wherein said pulsating portion is made from materials selected from the group consisting essentially of rubber, silicone, plastics, and polymers.

5. The chamber according to claim 1, wherein said pulsating portion includes entire said wall means, or portion thereof.

6. The chamber according to claim 1, wherein said pulsating portion is made from materials different from materials of said wall means.

7. A micro-fluidic pump comprising:

a micro conduit for carrying fluid therethrough; and

at least one actuating means for peristaltically moving fluids through said micro conduit, said actuating means includes a closed pocket adjacent to said conduit, flexible means defining a portion of a wall of said micro conduit, and expanding means disposed within said pocket for expanding a volume of said pocket and thereby flexing said flexible means into said micro conduit thereby changing the volume of said conduit.

8. The micro-fluidic pump according to claim 7, wherein said flexible means is made from material selected from the group consisting essentially of silicon rubber, rubber, PVC, polyurethane, polymers, and combinations thereof.

9. The micro-fluidic pump according to claim 7, wherein said expanding means includes vaporizable fluid selected from the group consisting essentially of water, wax, hydrogel, and hydrocarbon.

10. The micro-fluidic pump according to claim 7, further including a series of said actuating means working in tandem to peristaltically move fluids.

11. The micro-fluidic pump according to claim 10, wherein said series of actuating means are operatively connected by said micro conduit.

12. The micro-fluidic pump according to claim 7, wherein said actuating means further includes heating means for inducing expansion of said expanding means into said micro conduit.

13. The micro-fluidic pump according to claim 7, that is fabricated using techniques compatible with low temperature, planar fabrication techniques.

14. The micro-fluidic pump according to claim 7 further including integrated circuitry for controlling said actuating means.

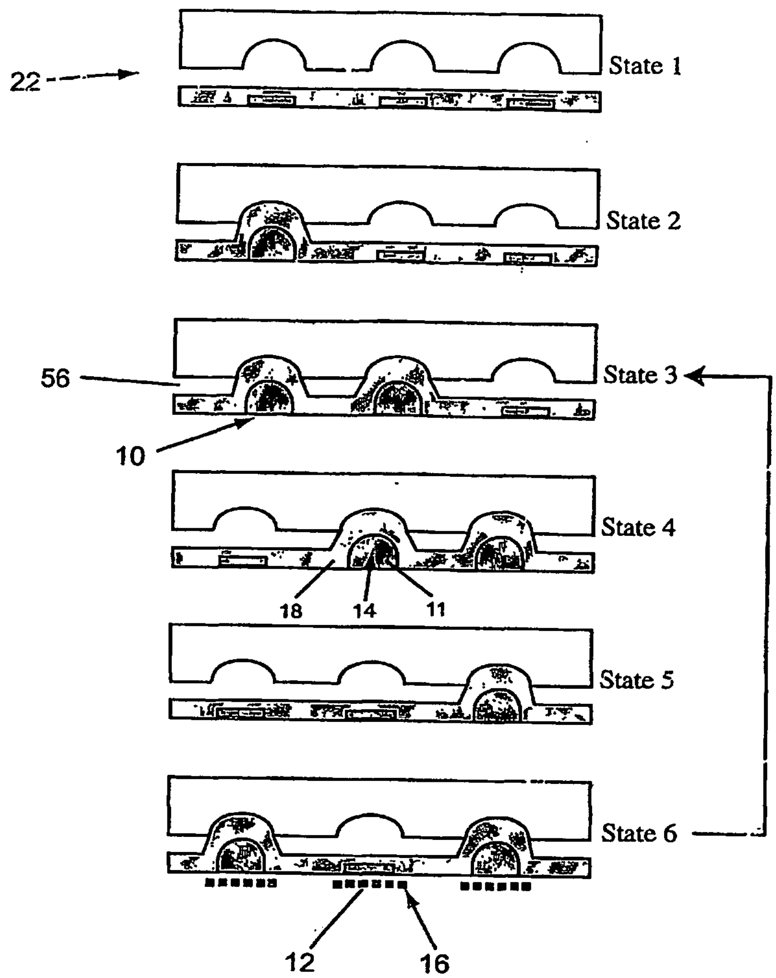

22
State 1
State 2
56
State 3
10
State 4
18
14
11
State 5
State 6
12
16

Figure 1.

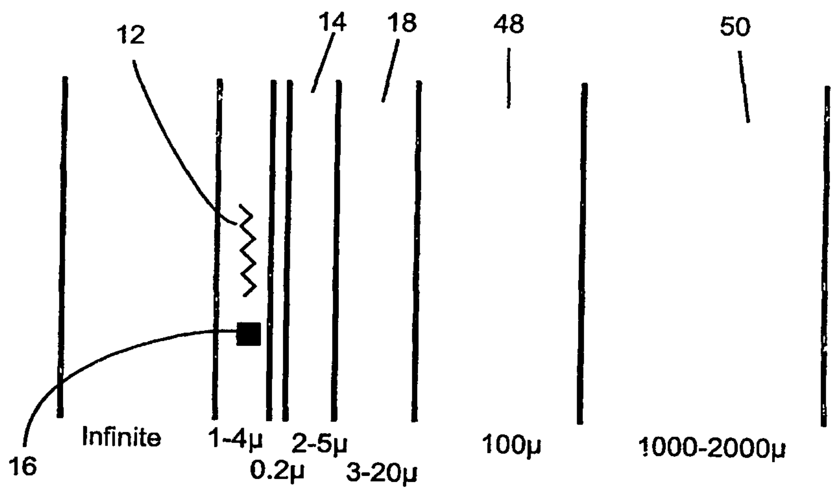


Figure 2.

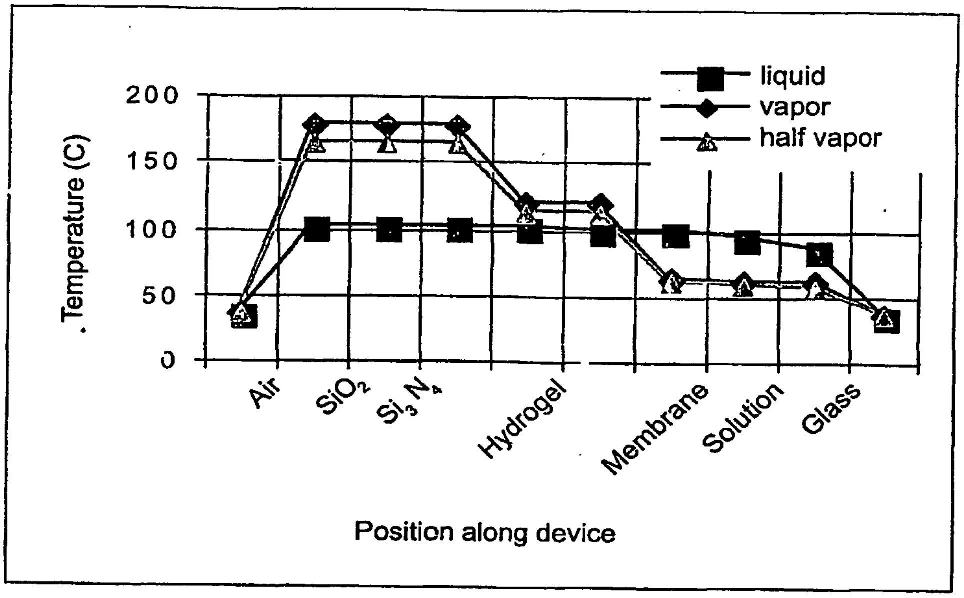


Figure 3.

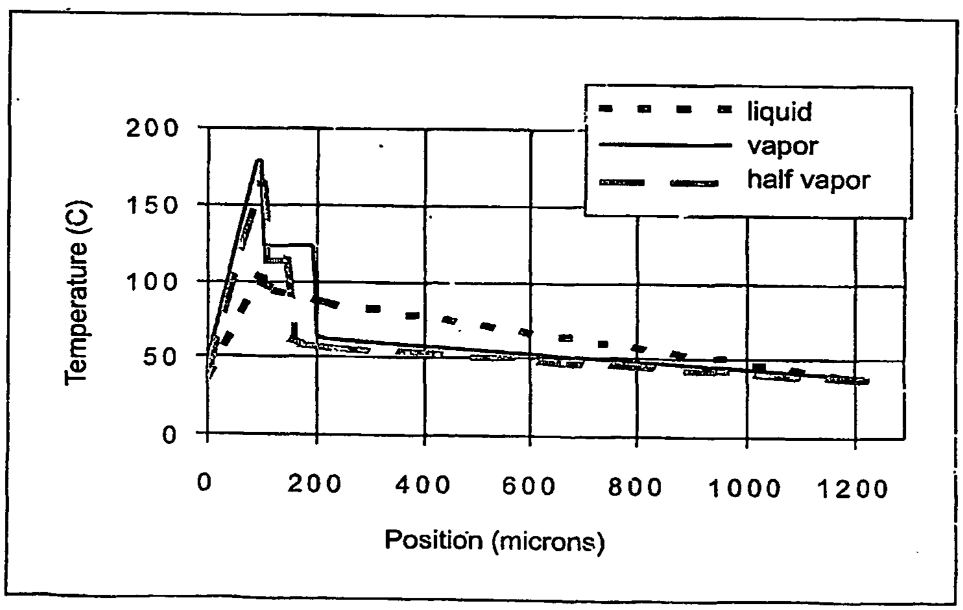


Figure 4.

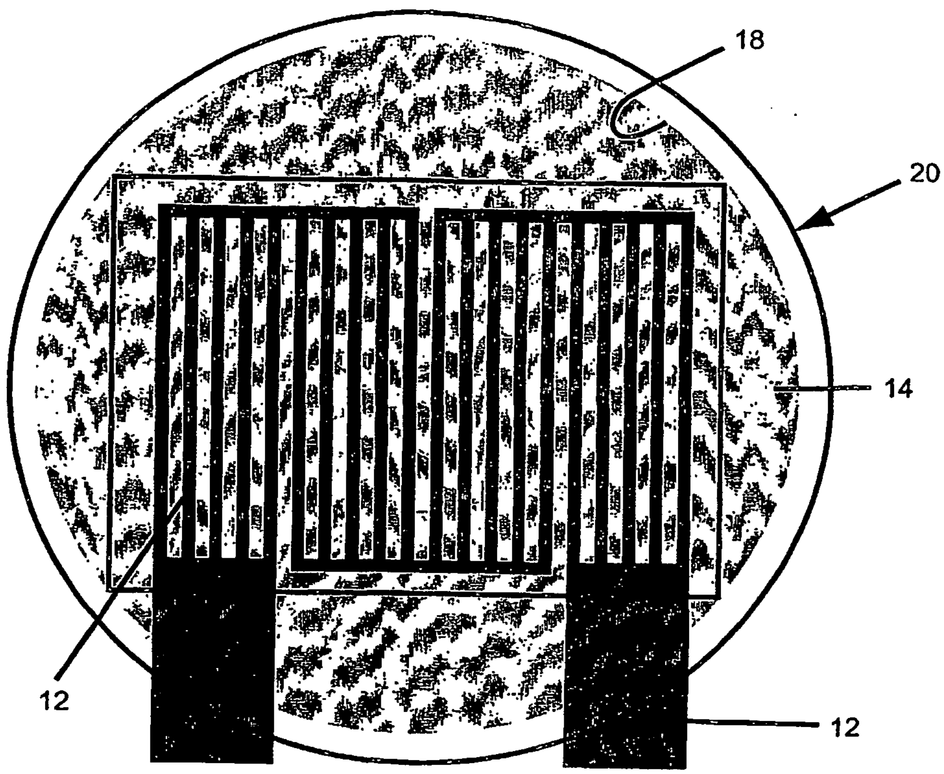
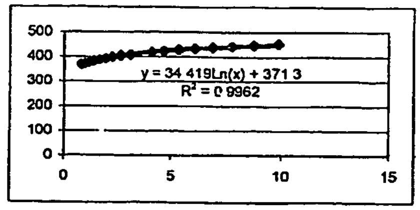


Figure 5.

Temp C	Temp K	Pressure kPa	Pressure atm	Temp K
95	368.15	84.55	0.834443622	368.15
100	373.15	101.35	1.000246731	373.15
105	378.15	120.82	1.192400691	378.15
110	383.15	143.27	1.413964964	383.15
115	388.15	169.06	1.668492475	388.15
120	393.15	198.53	1.959338761	393.15
125	398.15	232.1	2.290648902	398.15
130	403.15	270.1	2.665679743	403.15
135	408.15	313	3.089069825	408.15
140		316.3		413.15
145	418.15	415.4	4.09967925	418.15
150	423.15	475.8	4.695780903	423.15
155	428.15	543.1	5.359980262	428.15
160	433.15	617.8	6.097211942	433.15
165	438.15	700.5	6.913397483	438.15
170	443.15	791.7	7.813471503	443.15
175	448.15	892	8.803355539	448.15
180	453.15	1002.1	9.889958056	453.15
190	463.15	1254.4	12.37996546	463.15
200	473.15	1553.8	15.33481372	473.15
225	498.15	2548	25.14680484	498.15
250	523.15	3973	39.21046139	523.15
275	548.15	5942	58.64298051	548.15
300	573.15	8581	84.68788552	573.15



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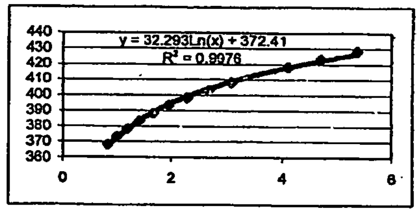

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Figure 6.

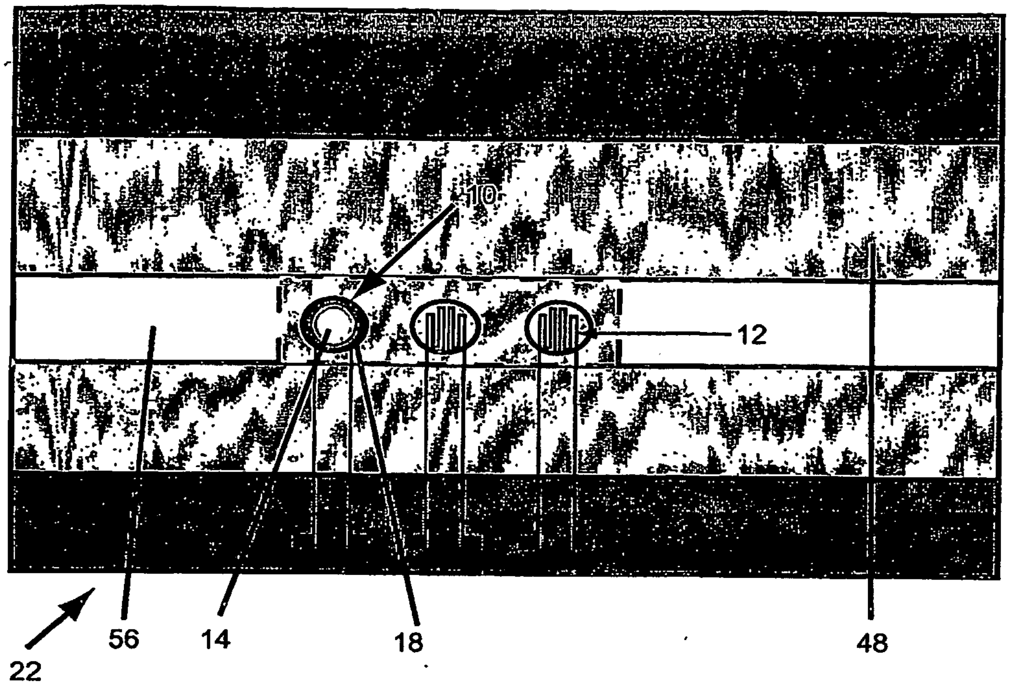
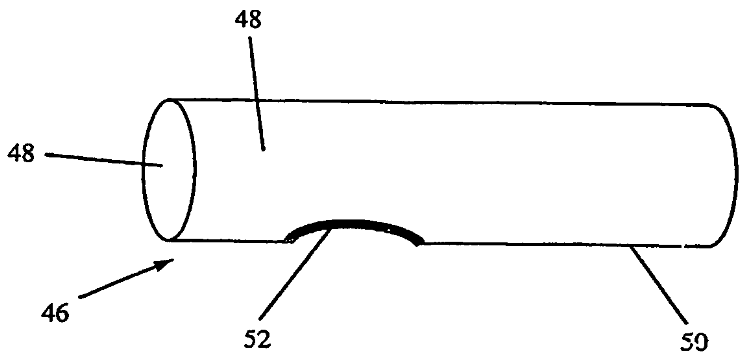


Figure 7.



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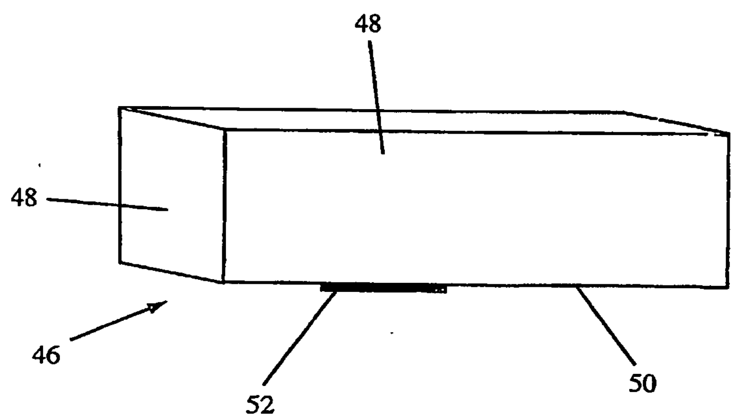

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Figure 8.

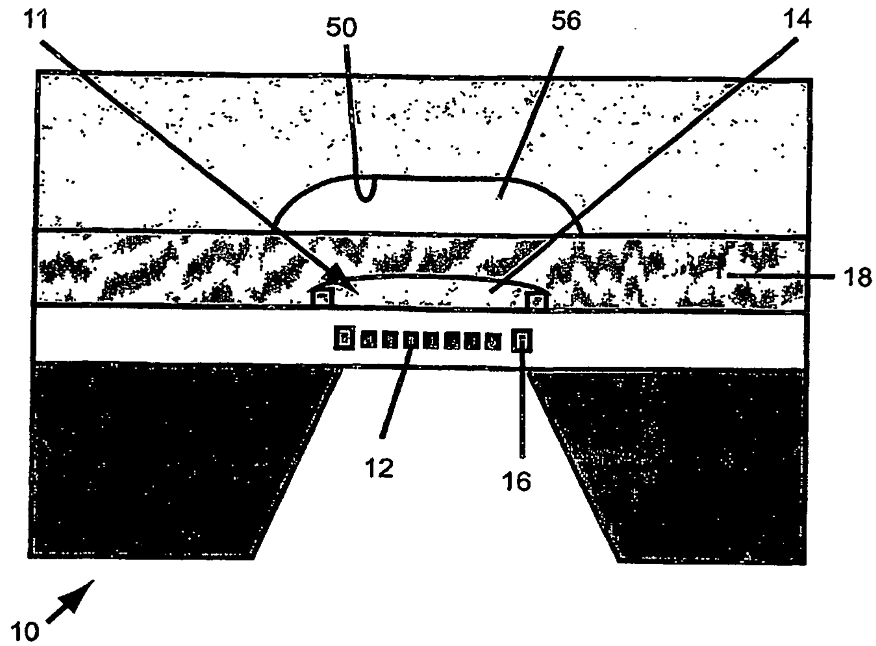

Figure 9.